

Comparison of Fault Diagnostics on Z-Source and Trans Z-Source Inverter Fed Induction Motor Drives

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Abstract

This paper investigates the performance of Trans Z- source inverter (abbreviated as T ZSI) fed induction motor drive under various fault conditions. With development in power electronics and remarkable improvement in control techniques, induction motor has evolved as a variable speed machine. For critical applications, continuous operation of the drive is of paramount importance. However, their performance is restricted by electrical and mechanical faults. When any fault occurs, the phase and line voltages of the inverters get decreased. This leads to reduction of torque and speed of the motor and hence the operation of induction motor is interrupted. This states the importance for fault diagnosis of T Z-Source inverter fed induction motor to analyse the performance of the drive under faulty conditions. The performance of the induction motor under various faults is verified by MATLAB simulation of a 5 Hp induction motor fed by a high performance ZSI and the simulation results are presented. A comparative evaluation of Z-source and T Z-source topologies is done for the same load torque conditions.

Keywords: AC Motor Drives, Fault Diagnosis, T Z-source, Z-source Inverter

1. Introduction

70% of the industrial drive applications use induction motors due to their high power-to-weight ratio, low price and easy maintenance. With development in power electronics and remarkable improvement in control techniques, induction motor has evolved to variable speed machine. Currently, three-phase Pulse Width Modulation (PWM) inverters are utilized in a variety of industry applications such as variable speed electric motor drives, uninterruptible power system, active power filters, and more recently, in renewable energy conversion systems and hybrid vehicles. Power inverter converts Direct Current (DC) to Alternating Current (AC). The converted AC can be made available at any required voltage and frequency with the use of appropriate transformers, switching, and control circuits. Traditionally, inverters are broadly classified into two types, such as Voltage Source Inverter (VSI) and Current

Source Inverter (CSI). The VSI can be used for buck (step-down) operation in DC-AC power conversion or for boost (step-up) operation in AC-DC power rectification, without any additional DC-DC converter to buck/boost the DC-link voltage. Similarly CSI can be only suitable for boost DC-AC power conversion or AC-DC power rectification. So for applications, where a wide range of voltage is desirable, an additional DC-DC converter is needed to meet the requirements.

The ZSI¹, has the unique feature that it can boost the DC voltage by allowing the shoot-through operating mode, and to produce any desired output AC voltage, even greater than the line voltage, regardless of the input voltage (between zero and infinity). The shoot-through state is forbidden in traditional PWM inverters since it results in short-circuit. Thus ZSI overcomes the limitations of two stage power conversion concept of the traditional inverters. In this work, the impedance source inverter is applied for adjustable speed drive applications.

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When induction motor is used as a drive for critical applications, operation of drive is of paramount importance and continuous operation of the system must be ensured. In spite of the technical development, inverters are often exposed to unexpected faults due to high stresses, misfiring, etc., affecting the operation of the entire system. When any of the faults occurs, the phase and line voltages of the inverter get decreased. This will lead to reduction of torque and speed of the motor and the motor stops its operation. Therefore, to preclude the harmful influence and system reliability, fault diagnosis has gained a lot of importance.

Available literature focuses on fault diagnosis of VSI fed induction motor drive. Schemes based on the inherent redundancy of voltage vectors were proposed in². The thermal behaviour of a three-phase induction motor was analysed in³. The motor thermal profile was obtained through the use of nine thermocouples positioned in both stator and rotor circuits. The experimental results obtained under fault compensated operation proved that it was not necessary to reinforce the motor insulation properties. A new fault-tolerant operation method for a symmetrical six-Phase Induction Machine (6PIM) was modelled. This model³, illustrated a dedicated test-rig to confirm the validity and the efficiency of the proposed method based on the reduction in the pulsating torque and the motor losses. Various compensation methods⁴, for three-level Z-source inverters under semiconductor-failure conditions which involves reconfiguring their relevant gating signals so as to ride-through the failed semiconductor conditions smoothly without any significant decrease in their AC-output quality and amplitude. Several fault tolerant strategies: switch redundant topology, four leg topology and phase redundant topology which provide compensation for open circuit and short circuit failures on semiconductor devices and soft commutation between redundant and main switches was presented in^{5,6}. A new method based on the formulation of diagnostic variables from average absolute values for real-time diagnostics of multiple open-circuit faults in VSI feeding AC machines was developed^{7,16}.

A sensor fault detection and isolation unit⁸ for induction motor drives based on an adaptive observer identifies the faulty sensor type based on a deterministic rule base. In⁹, a fault tolerant operating strategy based on the connection of the faulty inverter leg to the DC link middle point for a three phase induction motor was presented. The proposed Trans Z-source inverter¹¹, is based on transformers to produce a very high boost

voltage gain when the turn ratio of the transformers is larger than 1. The above literature does not deal with fault diagnostics of T ZSI based induction motor. The above literature does not compare the fault diagnostics on ZSI and TZSI based induction motor drives. The objective of this work is to fill this void by presenting a clear analysis of all the possible faults that may occur in a drive system. A comparison is made with the analysis of ZSI and T Z-source inverter fed induction motor under faulty conditions to prove that the impedance network reduces the harmonics developed due to the occurrence of the faults and T Z-source network reduces the size of the system.

The next section of this paper deals with analysis of Z-Source inverter with simple boost control technique. Section 3 explains the characteristics of the T Z-source inverter. Various types of faults and the performance of the motor during faulty conditions are analyzed in section 4. With the formulas derived in section 2, the design calculations are given in section 5. To test the proposed method, open-circuit and short-circuit faults are introduced in the ZSI fed induction motor drive. Simulation results are presented in section 6. Finally, the derived conclusions are presented in section 7.

2. Z-Source Inverter

The Z-Source network (circuit) consists of two inductors and two capacitors connected in a special arrangement to form a two-port impedance network. This combined circuit is the energy storage/filtering element for the Z-source inverter⁹. Based on this unique Z-source network, several power converters/inverters have been presented to overcome the limitations and problems of the traditional voltage-source and current-source converters, to provide the advantageous buck and boost function, and to improve reliability and performance¹⁰. The Z-source network shown in Figure 1 can be short and open circuited on either side. Therefore, the Z-source concept can be generalized as to provide a two-port network (or circuit) that can be short and open circuited at any time according to operation needs.

2.1 Shoot-Through Mode

ZSI has an extra state (shoot through) when both the upper and lower switches in a branch conduct at the same time, i. e. the Z-source is in short circuit. The shoot-through

state might be applied in seven different ways, i. e. Shoot-through by one branch which gives three combinations, shoot-through by two branches which also give three combinations and shoot-through by all three branches at once. The shoot-through state makes it possible to boost up the DC

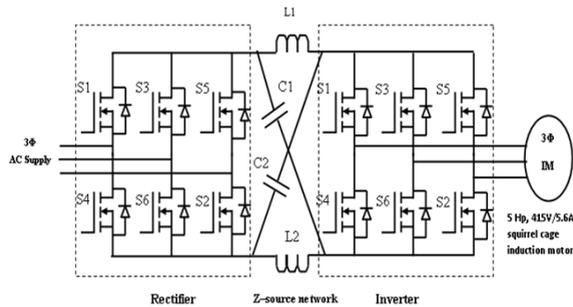


Figure 1. Z-Source inverter.

Input voltage. In traditional VSI, the shoot-through state would destroy the switches of the inverter bridge as all the stored energy of the system would be dissipated in the switches¹².

In ZSI the shoot-through state has no damaging effect as the energy stored in the capacitors is transferred to the two inductors of the Z-source during this state. The possibility of using the shoot-through state may influence the triggering strategy of the switches in the inverter bridge¹³. Figure 2 shows switching waveform with the extra zero state (or vector) when the load terminals are shorted. In this mode the Z-network is separated from the DC supply and the capacitor charge the inductor.

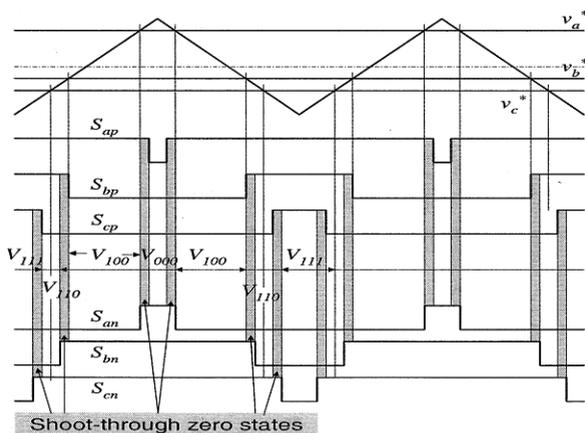


Figure 2. Modulation of shoot-through pulses.

3. Trans Z-Source Inverter

Voltage-type T (Trans) Z-source inverters uses a unique T-shaped impedance network for boosting their output voltage in addition to their usual voltage buck behaviour. Comparing it with traditional Z-Source topology, T Z-source inverter uses lesser components and a coupled transformer for producing the high-gain and modulation ratio simultaneously¹⁴. The obtained gain can be tuned by varying the turns ratio of the transformer within the narrow range of $1 < k \leq 2$. This leads to lesser winding turns at high gain which reduces the size of the system, as compared to other related topologies.

For Trans Z-source inverter, the two inductors in classical Z-Source topology are replaced by the transformers. Figure 3 consists of two transformers (T_1 and T_2), two capacitors (C_1 and C_2) and a diode D_{in} . The turns ratio of the transformers are defined as $k = n_{i2}/n_{i1}$, where $i = 1$ and 2 represent the transformers T_1 and T_2 respectively¹⁵. The main characteristics of T Z-Source inverter are as follows:

- The basic X-shape structure is retained.
- Only two transformers are used, and a very high boost factor can be obtained by changing the transformer turns ratio.
- Although producing a high boost factor, the T Z-source inverter does not use any additional diodes, which reduces its size, cost, and loss compared to original high boost Z-source inverter.

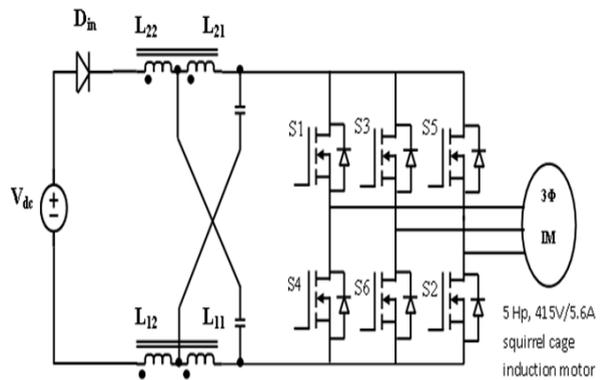


Figure 3. T Z-source inverter fed IM drive.

The boost factor of this inverter is increased to:

$$B = \frac{1}{1 - (1+n)\frac{T_o}{T}} = \frac{1}{1 - (1+n)D}$$

4. Design Calculations

The purpose of the inverter system is to produce a three-phase 230 V rms or 325 V peak from a DC source of 220V. The Simulink models of ZSI and T ZSI are developed based on the system parameters given in Table 1 and 2.

The design calculations for the above requirement are as follows:

Boost factor is given by, $B = \frac{1}{1 - 2\frac{T_o}{T}} = 2.5$

Shoot-through duty ratio, $\frac{T_o}{T} = D_o = 0.3$

The average DC-link voltage is given by,

$$V_{c1} = V_{c2} = V_c = \frac{1 - \frac{T_o}{T}}{1 - 2\frac{T_o}{T}} V_{dc} = 1.75 * 220 = 385V$$

Peak DC-link voltage is calculated using (2),

$$\widehat{v}_1 = B.V_{dc} = 2.5 * 220 = 550V$$

The peak output voltage is,

$$\widehat{v}_{ac} = M_a * B * \frac{V_{dc}}{2} = 0.7 * 2.5 * 110 = 192.5V$$

RMS AC output voltage, $V_{ac} = 136.1V$

Output line to line rms voltage = 236V

The buck-boost factor = $BB = 0.7 * 2.5 = 1.75$

Table 1. Specification of parameters of ZSI fed IM drive

Parameter	Specification
M_a	0.8
D_o	0.2
f_s	7500Hz
$L_1=L_2$	8mH
$C_1=C_2$	1000μF
V_{dc}	220V

Table 2. Specification of parameters of T ZSI fed IM drive

Parameter	Specification
M_a	0.8
D_o	0.2
f_s	7500Hz
$L_1=L_2$	10.5nH
L_m	10.4nH
$C_1=C_2$	1000μF
V_{dc}	220V

5. Simulation Results

The modeling and simulation of Trans ZSI based drive system was carried out using the Matlab/Simulink ¹⁷. The following waveforms show the simulation results of T Z-source network (open loop) with the following specifications listed in Table 1. For a traditional inverter, to obtain the output voltage of 230Vrms with modulation index of 0.7, 565V DC voltage is required. This is undesirable since it will require additional voltage booster circuit ¹⁸. Figure 5 shows input DC voltage applied to Trans Z-source inverter. The capacitor voltage is the average DC link voltage which remains almost constant as shown in Figure 6. Thus the input voltage (220V) is boosted to 378V and is applied as DC link voltage to the inverter. The peak value of this DC link voltage appears as input voltage across the main inverter circuit.

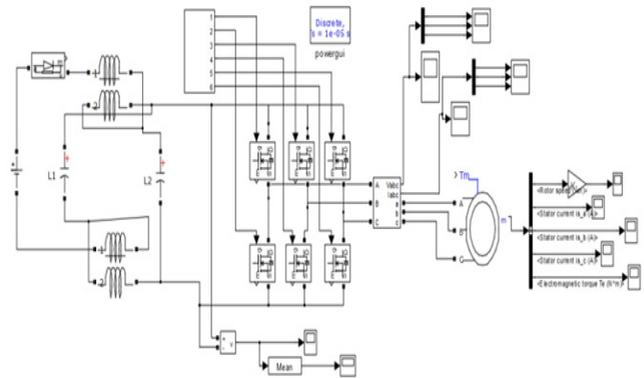


Figure 4. Simulink model of T Z-source inverter fed IM drive.

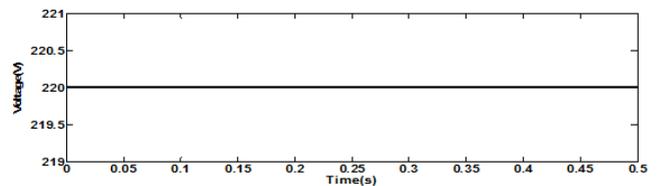


Figure 5. Input voltage.

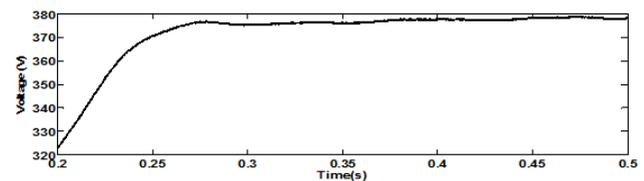
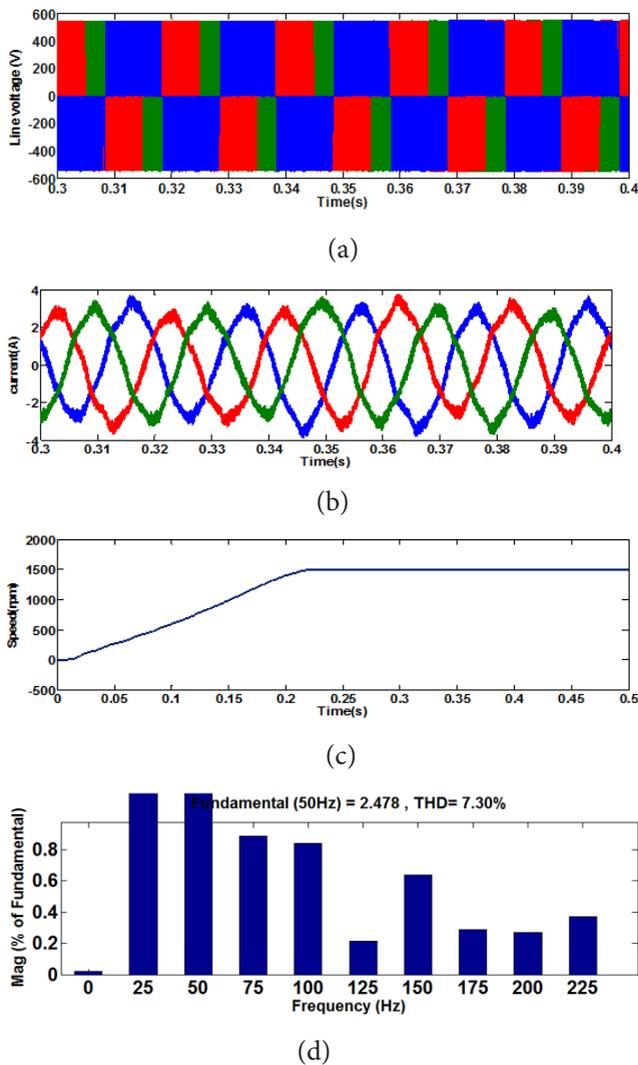


Figure 6. DC-link voltage.



The stator voltage and current are shown in Figures 7a and 7b respectively. The speed response is shown in Figure 7c. The speed increases and settles at 1480 rpm.

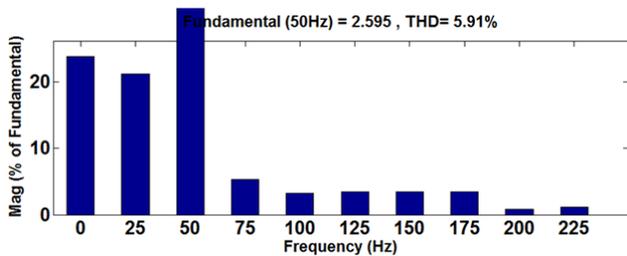


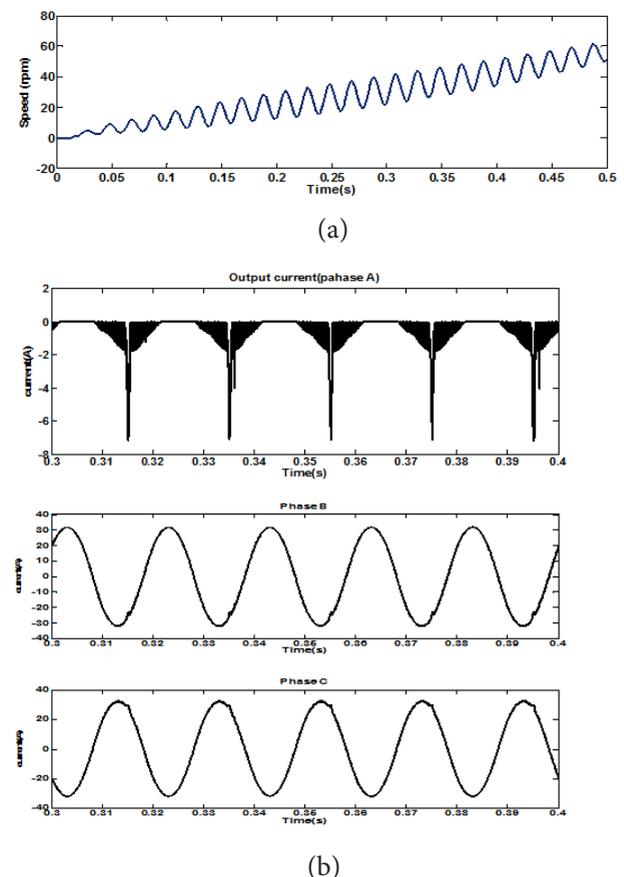
Figure 7. (a) Stator voltage under healthy condition. (b) Output current under healthy condition. (c) Speed response under healthy condition. (d) Line spectrum of Z-source inverter under healthy condition. (e) Line spectrum of T Z-source inverter under healthy condition.

The line spectrum under the healthy condition is shown in Figure 7d. The THD value in all the three phases is 7.30% in ZSI and 5.91% for T ZSI.

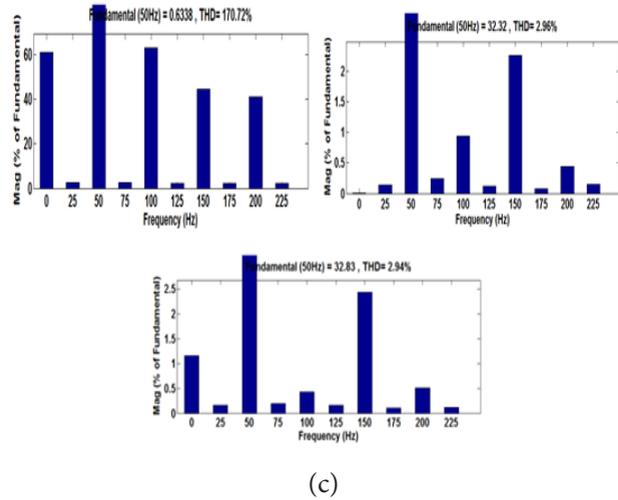
Although the technology development in power electronics has already achieved a certain level of maturity, due to their complexity and considering that inverters are often exposed to high stresses, unexpected faults may occur, influencing negatively the entire system¹⁹. In general, power device failures in the inverter can be broadly classified as open-circuit faults and short-circuit faults.

5.1 Single Device Open Circuit Fault

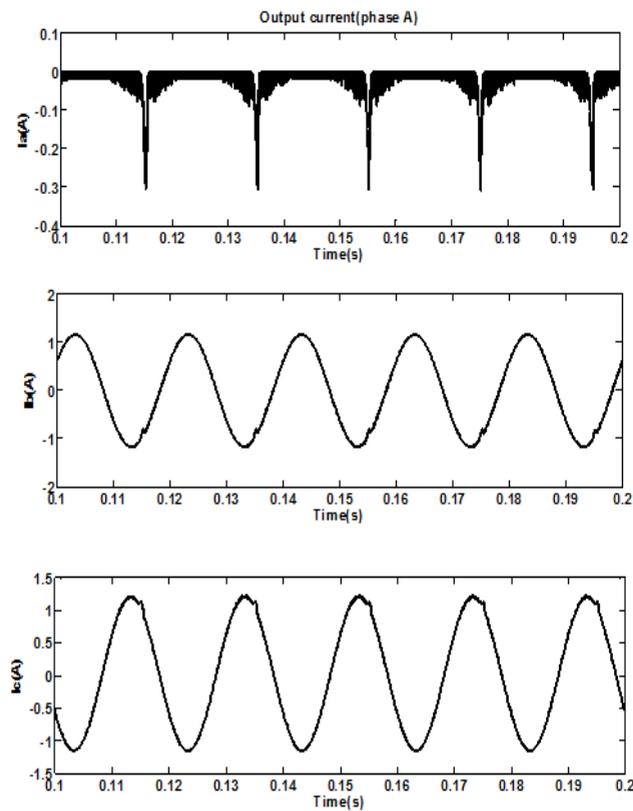
The upper switch of phase A is replaced with a high value of resistance to create an open circuit fault. This kind of failure will not necessarily cause the system shutdown and can remain undetected for an extended period of time²⁰. This may lead to secondary faults in the converter or in the remaining drive components, resulting in the total system shutdown and high repairing costs²⁴. From Figure 8, it is seen that the positive cycle of phase A voltage becomes zero since the current does not pass through a high resistance path. Speed never reaches the steady state value.



From the harmonic spectrum of the current waveforms, it is observed that the third harmonics are introduced due to faults.



(c)



(d)

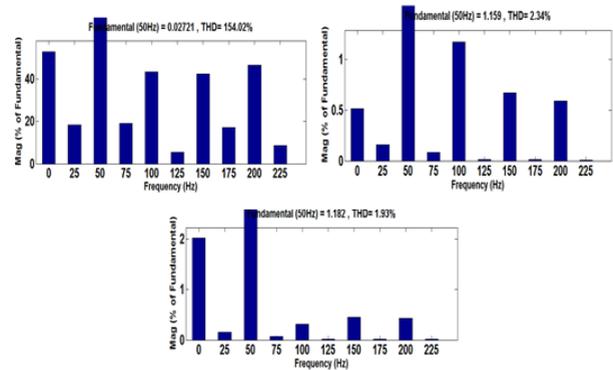
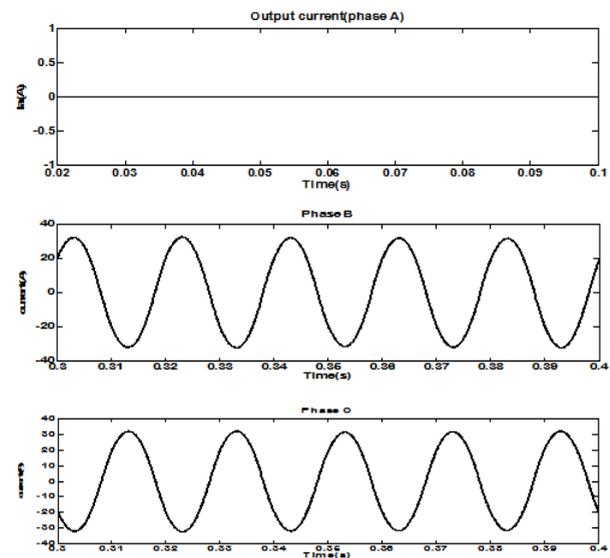


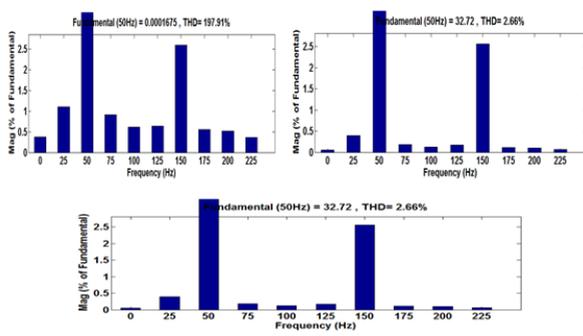
Figure 8. (a) Speed response under single device open circuit fault. (b) Output current waveforms of ZSI fed induction motor drive under single device open circuit fault. (c) Line spectrum of Z-source inverter under single device open circuit fault. (d) Output current waveforms of T ZSI fed induction motor drive under single device open circuit fault. (e) Line spectrum of T Z-source inverter under single device open circuit fault.

5.2 Single Phase Open Circuit Fault

When any one of the phase is replaced with high value of resistance the corresponding phase of the inverter gets disconnected from the motor²¹. The current through the corresponding phase is totally zero as shown in Figure 9 and the induction motor operates with the remaining two phases of the inverter. The motor stops and the operation gets interrupted.

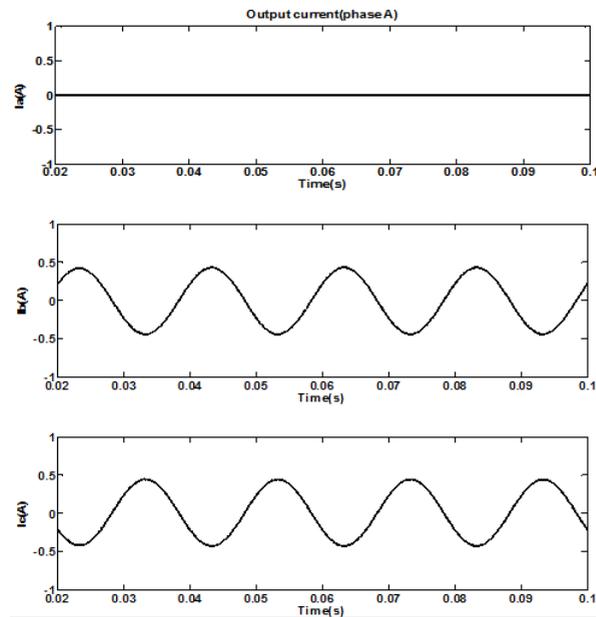


(a)



(b)

From the current waveforms it is clear that the fault current is comparatively reduced in Trans Z-Source inverter.



(c)

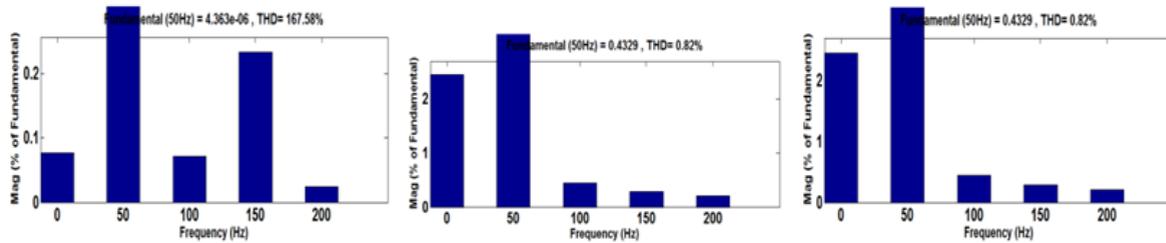
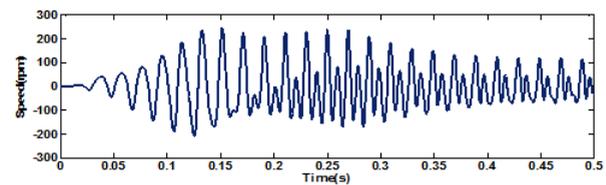


Figure 9. (a) Output current waveforms of ZSI fed induction motor drive under single phase open circuit fault. (b) Line spectrum of Z-source inverter under single leg open circuit fault. (c) Output current waveforms of T ZSI fed induction motor drive under single phase open circuit fault. (d) Line spectrum of T Z-source inverter under single leg open circuit fault.

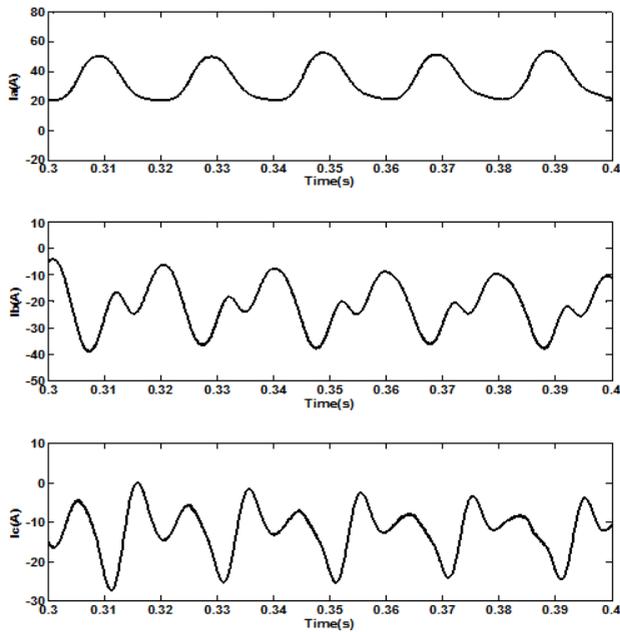
5.3 Single Device Short Circuit Fault

Short circuit fault is modelled by replacing any one of the MOFETs with a low resistance²². Under this condition the current flows through the short circuit path and thus the load gets disconnected from the circuit. In ZSI, the short circuit level is tolerable up to certain period depending on the duty ratio^{23,25}. If this period exceeds the duty ratio period, due to continuous conduction, the particular leg gets shorted and load gets disconnected from the supply. The current and speed response during short circuit fault are shown in Figures 10a, Figures 10b, Figures 10c, Figures 10d, Figures 10e respectively.

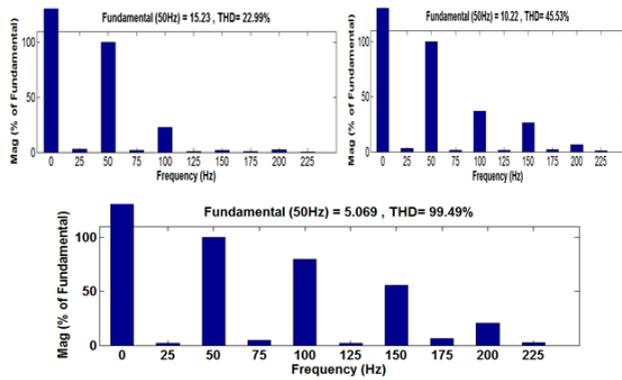
From the harmonic analysis it is seen that short circuit fault produces high DC component in the current spectrum and this DC component produces heating of the winding.



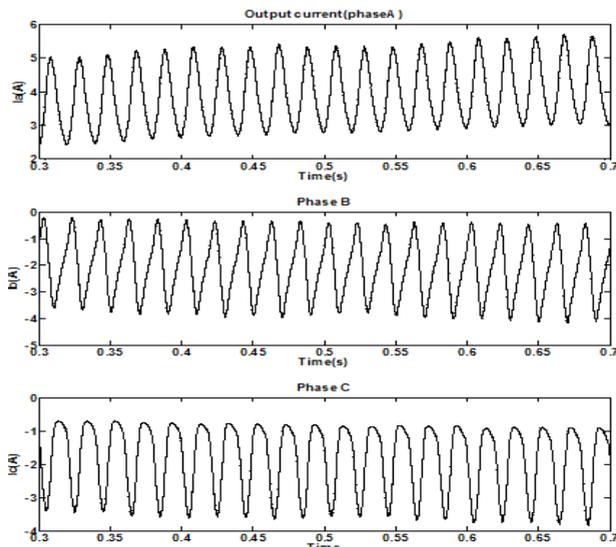
(a)



(b)



(c)



(d)

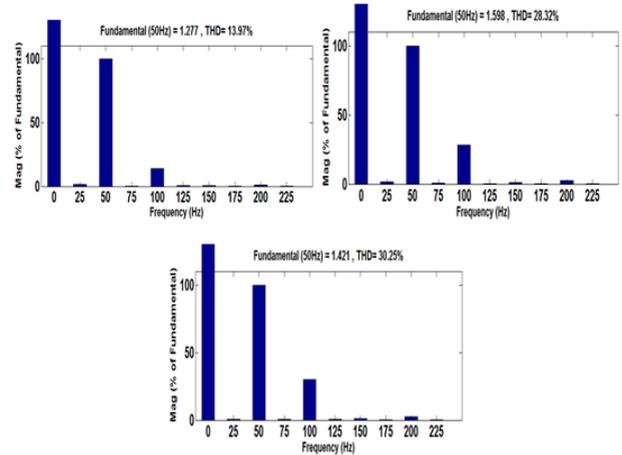


Figure 10. (a) Speed response under single device short circuit fault. (b) Output current waveforms of ZSI fed induction motor drive under single device short circuit fault. (c) Line spectrum of Z-source inverter under single device short circuit fault. (d) Output current waveforms of T ZSI fed induction motor drive under single device short circuit fault. (e) Line spectrum of T Z-source inverter under single device short circuit fault.

6. Conclusions

This paper has presented fault diagnosis of Trans Z-source inverter system. The T ZSI does a single stage power conversion with high boost factor compared to the traditional Z-source inverter. The paper described the operating principle and analyzed the possible faults that can occur in a drive system. Analytical and simulation results have been presented. The T Z-source inverters can boost-buck the voltage, minimize the component count, increase the efficiency and reduce the cost. During various fault conditions, the fault current and the speed of the motor are analyzed to show the effect of faults on the entire system. Comparison of the results in Table 2 shows that the total harmonic distortion in the T Z-source inverter fed induction motor is reduced by 30% when compared to the ZSI fed induction motor. Also the size of the system is much reduced with T Z-source inverter. The simulation results are in line with the predictions.

The disadvantage of TZSI is the requirement of two coupled inductors. The scope of this work is the modeling and simulation of ZSI and TZSI systems. The hardware will be done in future.

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